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UTICAJ SNAGE IZVORA TOPLOTE I BRZINE ZAVARIVANJA NA ZATEZNU CVRSTOCU HIBRIDNIH ZAVARENIH SPOJEVA

INFLUENCE OF HEAT SOURCE POWER AND WELDING SPEED ON THE TENSILE STRENGTH OF HYBRID WELDS

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Rezime:
Hibridni postupci lasersko-elektrolučnog zavarivanja široko se primenjuju za ostvarivanje visokokvalitetnih zavarenih spojeva kombinovanjem dva izvora toplote, čime se omogućavaju veća dubina penetracije i poboljšana mehanička svojstva spojeva. U ovom radu ispitan je uticaj snage laserskog snopa u opsegu od 11,5 do 13 (kW), brzine zavarivanja od 1,8 do 2,2 (m/min) i struje zavarivanja od 303 do 329 (A) na zateznu čvrstoću hibridnih lasersko-elektrolučnih zavarenih spojeva na konstrukcionom čeliku S355J2 debljine 12 (mm). Primenjen je multifaktorski eksperimentalni pristup radi analize pojedinačnih i interakcionih uticaja procesnih parametara. Dobijeni matematički modeli pokazuju da sva tri procesna parametra imaju statistički značajan uticaj na zateznu čvrstoću hibridnih zavarenih spojeva. Snaga laserskog snopa i struja zavarivanja pozitivno utiču na zateznu čvrstoću, dok brzina zavarivanja ispoljava negativan uticaj. Međutim, negativan efekat brzine zavarivanja može biti ublažen njenom pozitivnom interakcijom sa strujom zavarivanja, što dovodi do poboljšanja ukupnih performansi zavarenog spoja.

Ključne reči: hibridni zavareni spoj, zatezna čvrstoca, snaga laserskog snopa, struje zavarivanja

Abstract:
Hybrid welding processes are widely used to achieve high-quality joints by combining multiple heat sources, enabling deeper penetration and improved mechanical characteristics. This study investigates the influence of laser beam power 11.5–13 (kW), welding speed 1.8–2.2 (m/min), and welding current 303–329 (A) on the tensile strength of hybrid laser–arc welds on structural steel S355J2 with thickness of 12 (mm). A multi-factor experimental approach was applied. The mathematical models show that all three process parameters significantly influence the tensile strength of hybrid welds. Laser beam power and welding current have a positive effect, whereas welding speed exhibits a negative influence. However, the negative effect of welding speed can be mitigated through its positive interaction with welding current, leading to improved overall weld performance.

Key words: hybrid weld, tensile strength, laser power, welding current

1. INTRODUCTION

Hybrid Laser Arc Welding (HLAW) is an advanced welding process that combines the advantages of Laser Beam Welding (LBW) and semi-automatic welding processes such as Gas Metal Arc Welding (GMAW) or Flux-Cored Arc Welding (FCAW) in a single process. The simultaneous application of two heat sources enables high welding speeds, increased penetration depth, reduced heat input compared with conventional arc welding, and improved process productivity. Owing to these characteristics, HLAW has attracted considerable interest for welding of structural steels where high-quality welded joints, increased productivity, and reduced thermal distortion are required [1].

Despite its numerous advantages, the application of HLAW is associated with relatively high process complexity due to the combination of two heat sources and the large number of welding parameters that must be properly selected and controlled to achieve a stable welding process and acceptable weld quality [2]. The values of the parameters that are ideal for each process separately are not optimal for successful welding with HLAW. Previous research has demonstrated that HLAW parameters are not specified enough to replicate the conditions for a particular operation. Mainly, the weld quality and its geometry strongly depend on the ratio between the laser power and arc power [3]. The appropriate selection of this ratio is essential for achieving a stable weld pool and the required weld quality, which can be evaluated in terms of mechanical characteristics, microstructure, and weld bead geometry [4].

However, an inappropriate combination of laser and arc energy can result in significant weld imperfections. Among the most relevant defects associated with HLAW are humping and insufficient penetration, both of which can adversely affect the mechanical characteristics and fatigue life of the hybrid weld. The amount of heat input is the main factor directly related to these imperfections [5].

The influence of individual welding parameters on HLAW has been investigated in numerous studies. However, the simultaneous influence and interaction of several welding parameters remain an important research topic. In particular, the effects of laser beam power, welding speed, and welding current cannot always be evaluated independently because changes in one parameter modify the thermal conditions under which the other parameters act [6]. Therefore, a multi-factor experimental approach is required to identify the relative importance of the individual parameters and their interactions and how they influence on the weld mechanical characteristics.

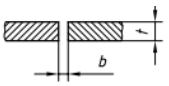
Accordingly, this study investigates the influence of the three main parameters – laser beam power, welding speed and welding current on the tensile strength of single-pass hybrid laser arc welds on structural steel with thickness of 12 (mm). Their influence are investigated using the multi-factor experimental design, in which the laser beam power is varied in the range of 11.5–13 (kW), the welding speed from 1.8–2.2 (m/min), and the welding current from 303–329 (A). Particular attention is given not only to the individual effects of the selected parameters but also to their mutual interactions.

2. MATERIALS AND METHODS

The welding experiments of the present study were conducted on 12 (mm) thick plates of structural steel in quality S355J2. The pieces were cut to dimensions 150 x 400 (mm) before welding preparation. The welds were produced in an I-joint configuration with zero root gap, with the joint edges prepared by milling, table 1. The welding wire used for HLAW was a solid wire G3Nil according to EN ISO 14341-A: G 42 3 M21 3Si1 with a diameter of 1.2 (mm). As a shielding gas is used a mixture of argon with 18% CO2 - CORGON 18 according to EN ISO14175: M21 ArC 18 with a flow rate of 25 (l/min). The base material

has a carbon equivalent value of max. 0.39 (CEIw for low alloy steels, CEIIW = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15).

Table 1. Preparation of joint edges in accordance with EN ISO 9692-1

Material	Thickness - t (mm)	Symbol ISO 2553	Drawings	Dimensions			Welding process ISO 4063	Weld illustration
				Angle	Width - b (mm)	Heigth - c (mm)		
S355J2+N	≤ 15	II		/	1 ≤ b	/	522	

A welding machine, Qineo Pulse 600 of Cloos, with a maximum current of 600 (A) was applied as a power source for the arc. GMAW was performed with a direct current of positive polarity (DC+). A high – power fiber laser IPG YLR-20000 of IPG was used in the experiments with the following parameters: an optical fiber with a 200 (mm), beam parameter product of 11 (mm×mrad), and 1070-nm wavelength. A laser processing head, BIMO HP, with a focal length of 350 (mm) providing a spot focus diameter (df) of 0.56 (mm) was used.

The laser optics and GMAW torch were mounted on the robot arm with an included angle of 25°, while the robot position remained unchanged throughout the welding process. Prior to welding, the plate edges were cleaned with acetone to remove grease and other contaminants. Tack welds were applied at both the beginning and the end of the plates to ensure the zero -gap of I-joint configuration. All experiments were performed using an arc-leading orientation, with a distance of 3 (mm) between the laser beam and the arc heat sources. The laser beam was focused at a position of −3 (mm) relative to the workpiece surface, while the wire stick-out was maintained at 15 (mm).



Figure 1. Positioning of the electrode wire and laser beam

The experiment was conducted to investigate the influence of three main welding parameters on the tensile strength of the hybrid weld. Therefore, a multifactor experimental approach was employed, and nine hybrid welds were welded according to the experimental matrix of the orthogonal method using a 2^3 design. This design involved varying the three independent variables at two levels, corresponding to their minimum and maximum values, with an additional central point included in the experimental design as a control point.

Accordingly, this study investigates the influence of the three main parameters – laser beam power, welding speed and welding current on the tensile strength of single-pass hybrid laser arc welds on structural steel with thickness of 12 (mm). The laser beam power is varied

in the range of 11.5–13 (kW), the welding speed from 1.8–2.2 (m/min), and the welding current from 303–329 (A).

The values of the independent variables and their ranges of variation within the experiment were determined based on the previous research. For a more convenient representation of the experimental conditions and processing of the experimental results, the variables were coded as follows:

1. X_1 - laser beam power, P_L(kW): 11.5 – 13 (kW);
2. X_2 - welding speed, V_z (m/min): 1.8 – 2.2 (m/min);
3. X_3 - welding current, I_z (A): 303 – 329 (A).

To determine the tensile strength of the hybrid welds, three test specimens were prepared from each hybrid weld at three different locations to perform three tests and obtain more accurate results. Based on previous research, the tensile strength of the hybrid weld exceeds that of the base material. Therefore, non-standard tensile test specimens were prepared with the weld face and root ground flush and with a square notch in the weld from both sides, figure 2 [7].

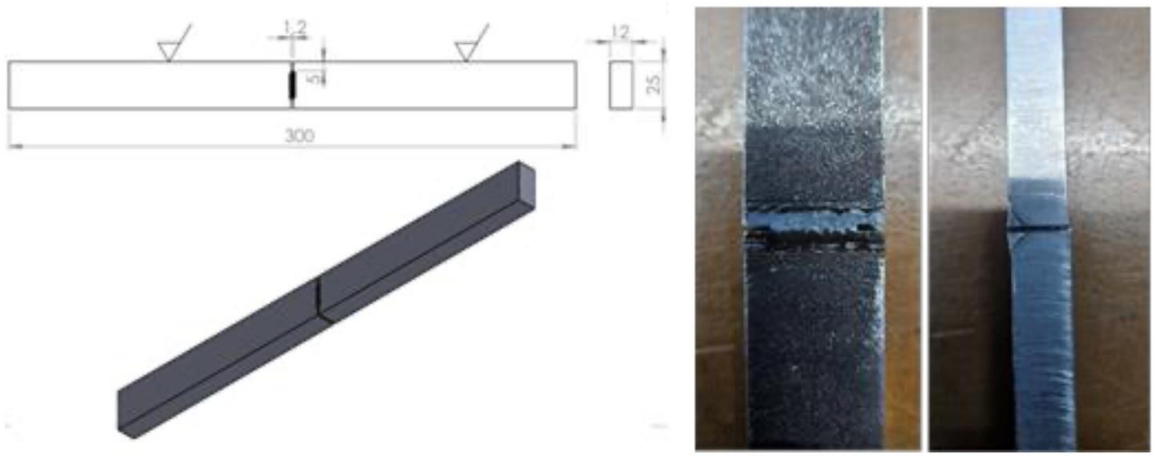


Figure 2. Non-standard specimen for tensile strength testing of the hybrid weld

3. RESULTS AND MATEMATICAL ANALYSIS OF THE EXPERIMENT

In Table 2 presents the experimental matrix for the 2^3 design, involving the variation of three independent variables at two levels, the minimum level (−1) and the maximum level (+1), together with the central point of the experimental design.

Table 2. Preparation of joint edges in accordance with EN ISO 969

Experiment number	Encoded values			Values of independet variables			Dependent variable
	X1	X2	X3	P_L (kW)	Vz (m/min)	Iz(A)	
1	-1	-1	-1	11.5	1.8	303	Y_1
2	1	-1	-1	13	1.8	303	Y_2
3	-1	1	-1	11.5	2.2	303	Y_3
4	1	1	-1	13	2.2	303	Y_4
5	-1	-1	1	11.5	1.8	329	Y_5
6	1	-1	1	13	1.8	329	Y_6
7	-1	1	1	11.5	2.2	329	Y_7
8	1	1	1	13	2.2	329	Y_8
9	0	0	0	12.2	2	316	Y_9

The output sizes represent the function of the response, also called the regression equation: $Y = f(X_1, X_2, X_3)$.

The adequacy of the model is verified by experimental results using the Fisher criterion at the confidence level of 95% and with 16 degrees of freedom [$N(n-1)=2^3(3-1)=16$]. A three factor experiment uses a regression model of the following form for the analysis of the mutual effect of individual factors:

$$Y = b0 + b1X1 + b2X2 + b3X3 + b12X1X2 + b13X1X3 + b23X2X3 + b123X1X2X3$$

After verifying the regression coefficients and the adequacy of the model, the significance of the coefficients of the regression model is determined using Student's t-test[8].

Table 3. Measured values for the experiment

Experiment number	Measured values for tensile strength (N/mm2)			Sum of values	Arithmetic mean	Variance of the results
1	688	679	675	2042	680.67	44.33
2	740	699	705	2144	714.67	490.33
3	574	610	614	1798	599.33	485.33
4	628	637	650	1915	638.33	122.33
5	706	719	732	2157	719	169
6	736	730	744	2210	736.67	49.33
7	676	671	661	2008	669.33	58.33
8	700	703	723	2126	708.67	156.33

The values of the regression model coefficients are:
b_0=683.3337, b_1=16.2512, b_2=-29.4187, b_3=25.0837, b_{12}=3.3337, b_{13}=-1.9988, b_{23}=10.0013, b_{123}=2.0837

According to Pantelic [9], for the Student's t-test at a 95% confidence level and 16 degrees of freedom we have 1.75, while the critical value of the coefficient (B_{kr}) is: 3.54450.

Based on the above, the applicable regression equation has the following form:

$$F_{cr} = 683.334 + 16.25X1 - 29.419X2 + 25.084X3 + 10.001X2X3$$

The calculated values of the tensile strength Rm for each experimental point are obtained by substituting the corresponding values of X1, X2, and X3 into the established regression model, as shown in Table 4.

Table 4. Model - calculated values of the tensile strength Rm

Experiment number	Measured values for tensile strength (N/mm2)			Model-calculated values (N/mm2)	Deviations (%)		
1	688	679	675	681.418	0.97	-0.35	-0.94
2	740	699	705	713.921	3.65	-2.09	-1.25
3	574	610	614	602.578	-4.74	1.23	1.90
4	628	637	650	635.081	-1.11	0.30	2.35
5	706	719	732	711.583	-0.78	1.04	2.87
6	736	730	744	744.085	-1.09	-1.89	-0.01
7	676	671	661	672.748	0.48	-0.26	-1.75
8	700	703	723	705.251	-0.74	-0.32	2.52

After checking the significance of the regression coefficients and the adequacy of the model, it can be concluded that the model is adequate, although not all of the coefficients are statistically significant. Transforming back to the natural coordinates, a decoded regression equation is obtained, which can be used to determine the influence of the independent variables on the tensile strength of the hybrid weld:

$$Rm = 2533.44 + 21.6683\ P_L - 1362.6360\ V_z - 5.7638\ I_z + 3.8467\ V_z\ I_z$$

4. CONCLUSIONS

Based on the experimental reserach and analysis of the obtained results, the following conclusions can be drawn regarding the influence of laser beam power, welding speed and welding current on the tensile strength of hybrid laser–arc welded joints of S355J2 structural steel:

1. The developed regression model was found to be adequate for describing the relationship between the process parameters and the tensile strength of the hybrid weld.
2. The laser beam power has a moderate positive effect, indicating that an increase in its value leads to an increase in the dependent variable, i.e., an increase in the tensile strength.
3. The welding speed has the strongest effect, which is negative, meaning that an increase in welding speed results in a decrease in tensile strength, assuming that the other independent variables remain constant.
4. The welding current has a positive effect on the dependent variable and represents the second most influential factor.
5. The interaction effect between welding speed and welding current is positive and statistically significant, indicating that the effect of welding speed is not constant but depends on the welding current.
6. Based on the regression model, to achieve high tensile strength values, it is recommended that the laser beam power and welding current be maintained at their highest levels, while the welding speed should be maintained at its lowest level.

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